Coatings and Surface Treatments for Reusable Entry Systems

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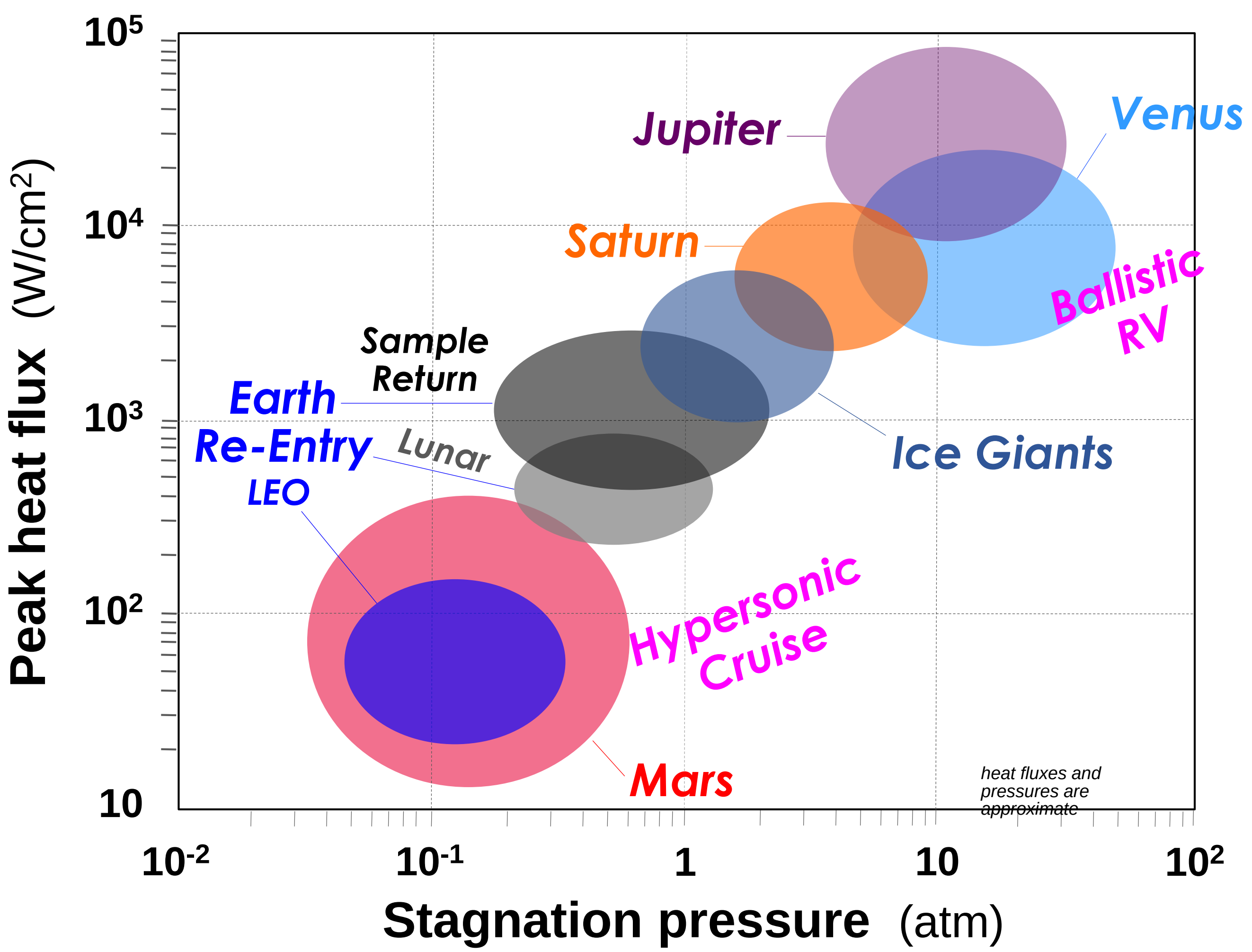
NASA & DoD Missions Requiring TPS



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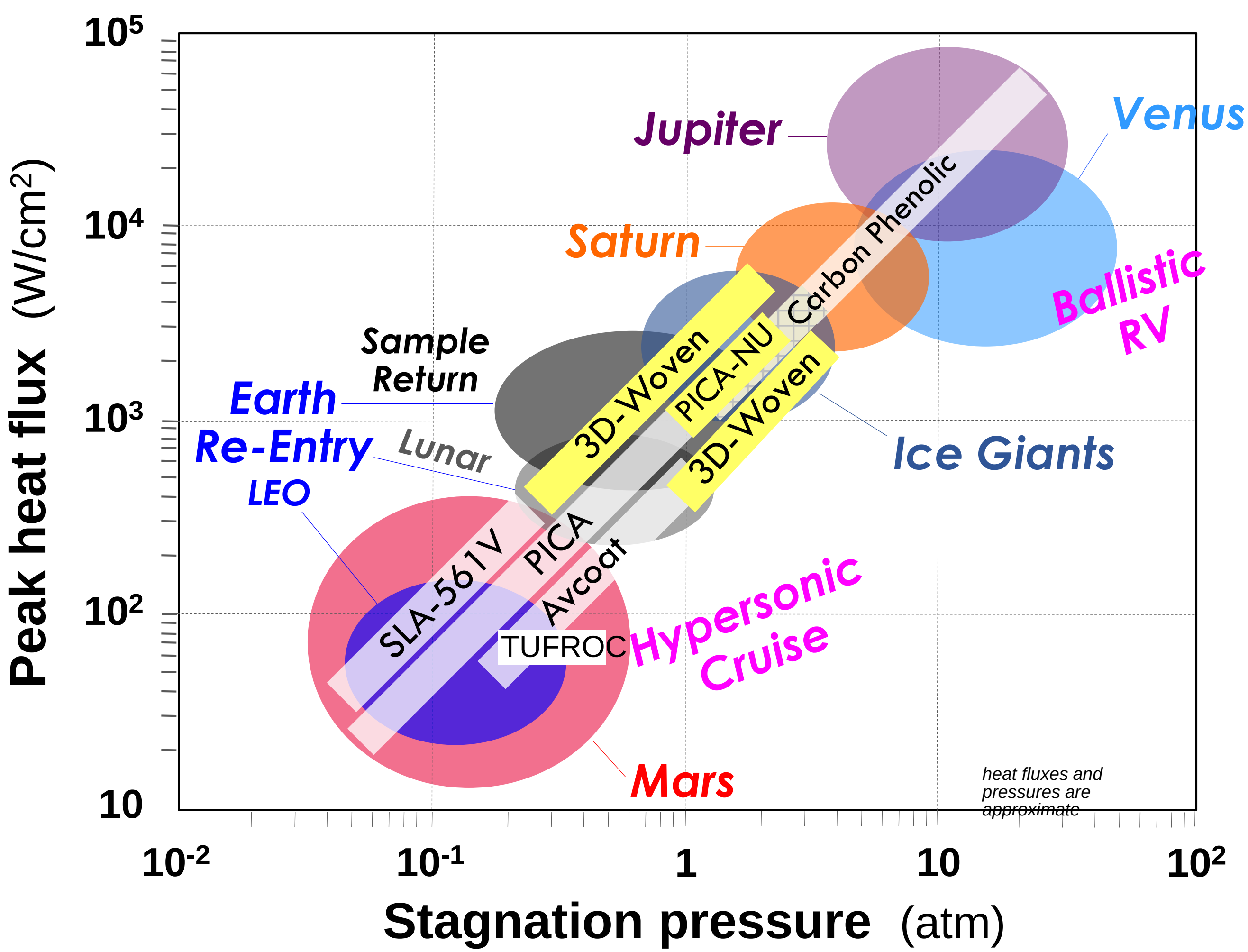


KEY

Flight Heritage TPS

Arc Jet Tested TPS

DoD Mission

RV Re-entry Vehicle

Reusable TPS and Ablators

Reusable TPS (definitions vary)

Material unchanged (mechanically, chemically) by the mission

TPS can be safely flown X number of times (with or without servicing)

TPS flew more than once

Ablators

Material is used up / depleted and recesses due to vaporizing, melting, subliming, spalling, erosion, and other ablative processes. Many ablative materials include constituents that pyrolyze and char, which help mitigates the heat load.

While any material can technically be reusable or an ablator – an effective TPS needs an optimized material stackup for all regions of the vehicle, factoring in all potential environments throughout the planned flight profiles and missions.

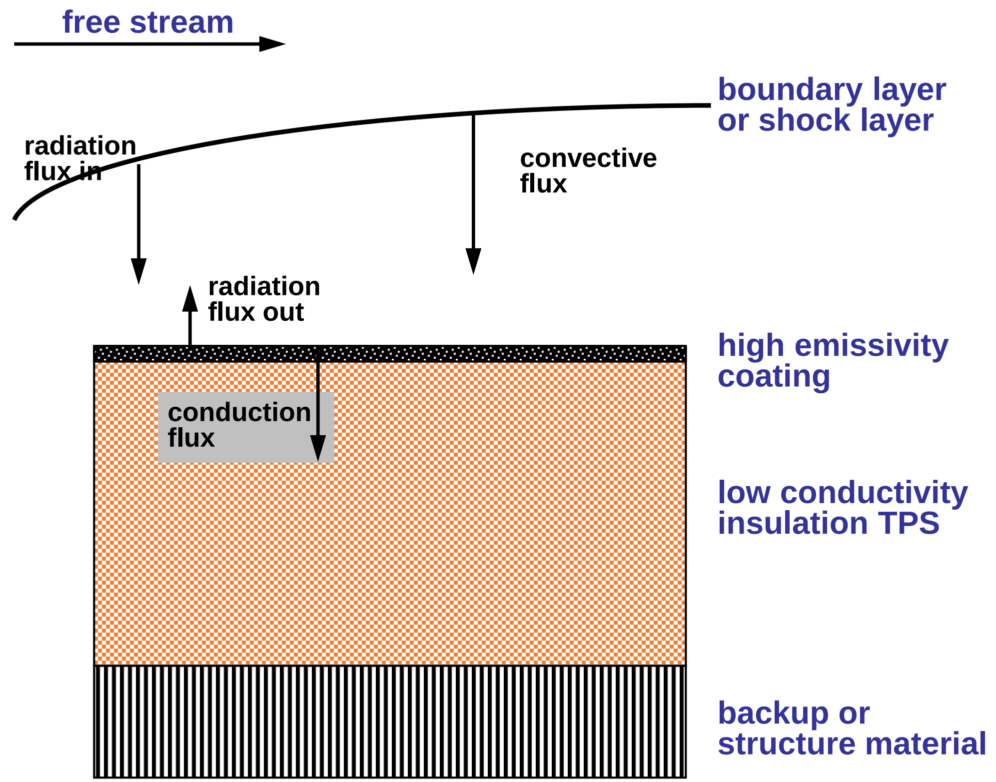
Note that many reusables can survive conditions beyond those for which they are designed and tend to fail

Insulative/Reusable TPS

Energy management through storage and re-radiation — material unchanged

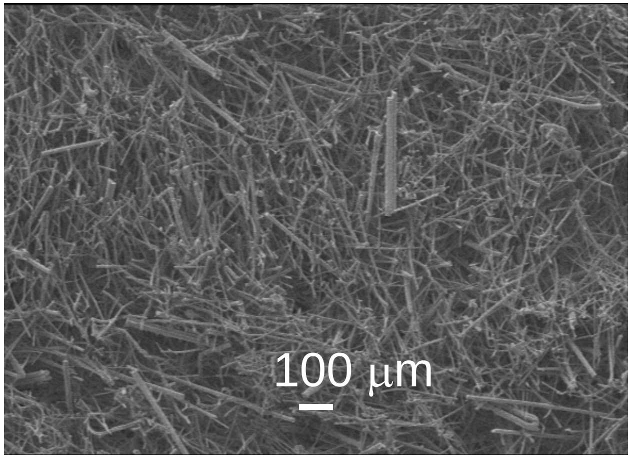
When exposed to atmospheric entry heating conditions, surface material will heat up and reject heat in the following ways:

- Re-radiation from the surface and internal storage during high heating condition
- Re-radiation and convective cooling under post-flight conditions



Reusable TPS Materials Requirements

- **High temperature capability**
- **High thermal shock resistance**
  (rapid heat-up with very large thermal gradients)
- **Properties stable over many flights**
- **Surface property requirements**
  - High emittance
  - Low catalycity
- **Low thermal expansion coefficient**
- **Low thermal conductivity**
- **Minimum weight heat shield**



AETB (35% Al_2O_3) Tile

Surface Treatments and Coatings

Coatings

Applied on top of a material, forming a separate layer

Surface Treatments

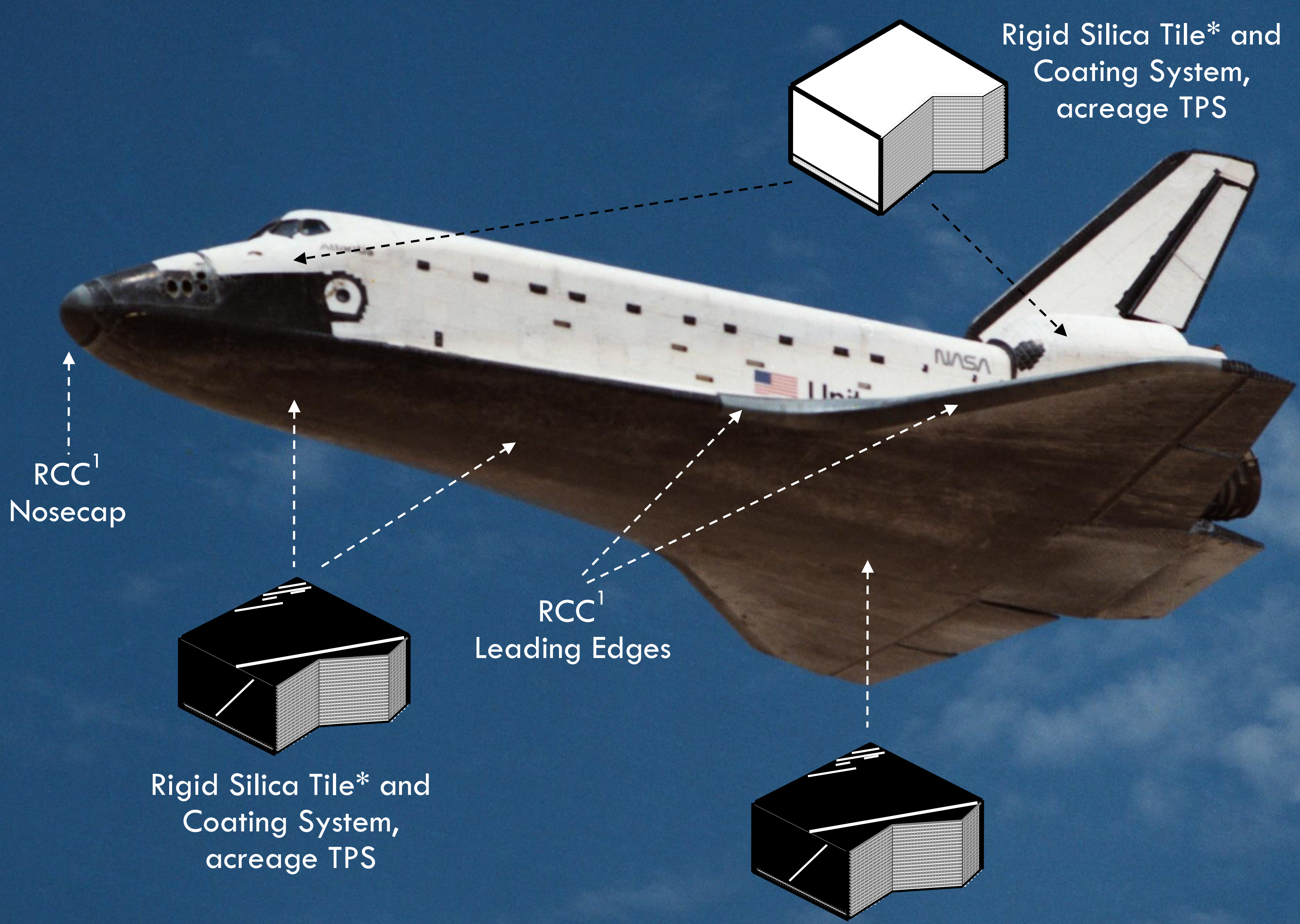
Deposited in the near surface forming an integrated or composite material

Surface treatments and coatings generally have the same goals

- *high temperature capability* to withstand nominal and abort environments
- *high emissivity* (> 0.9) except for areas where sunlight is the primary heat source
- *low catalycity* to avoid heating via chemical recombination of hot atmospheric/plasma constituents
- *mechanically stable* in the material system (high temperatures, thermal expansion, and thermal shock)

Water proofing is often desired for TPS that is exposed to water / high humidity

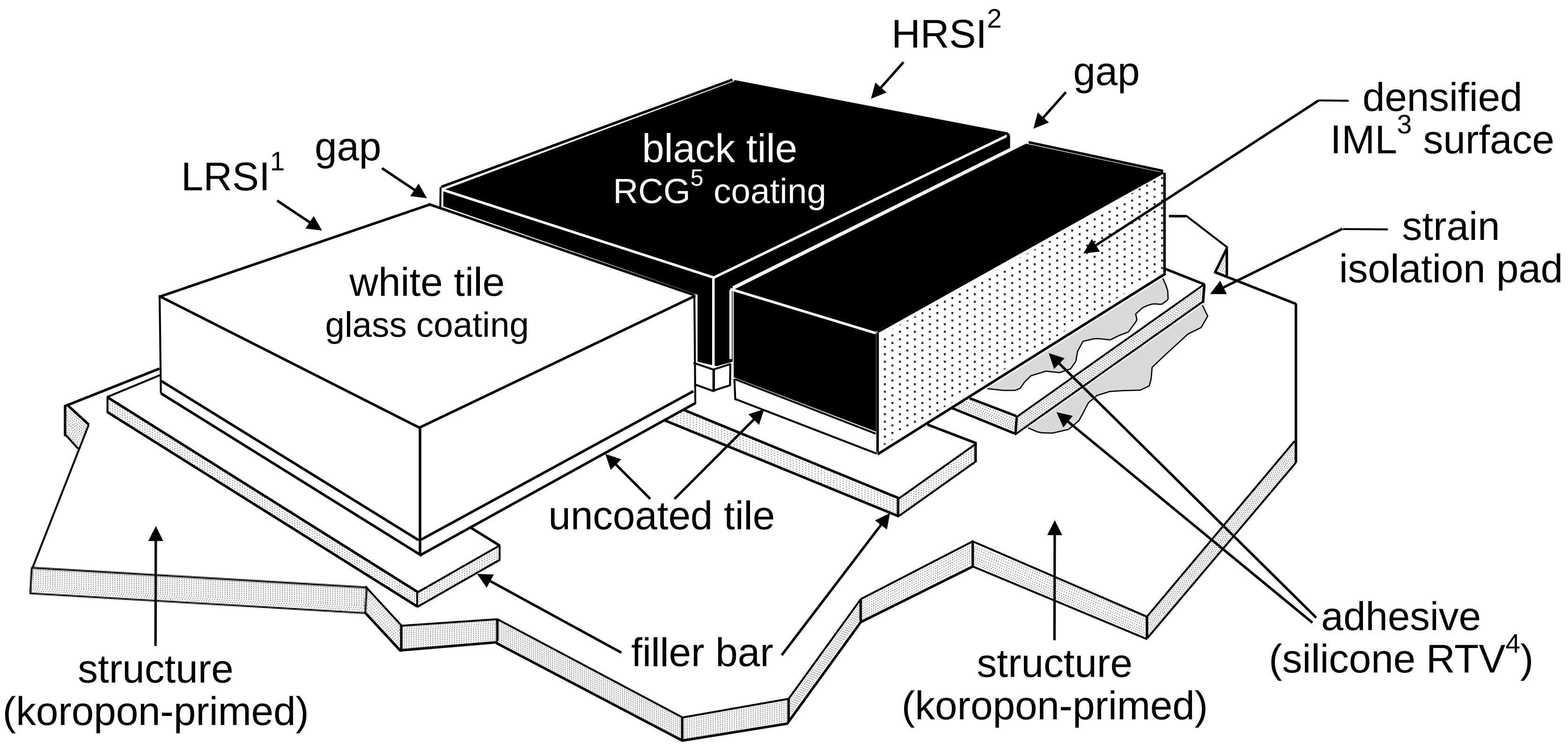
Original Space Shuttle TPS



*Developed by Robert Beasley
Lockheed Martin Missiles and Space

[1] Reinforced Carbon-Carbon

RSI Installation Configuration



1 Low Temperature Reusable Surface Insulation
2 High Temperature Reusable Surface Insulation
3 Inner Mold-Line
4 Room Temperature Vulcanizing
5 Reaction Cured Glass

STS-123 OV-105 Pre-Flight 21 External Tank Door

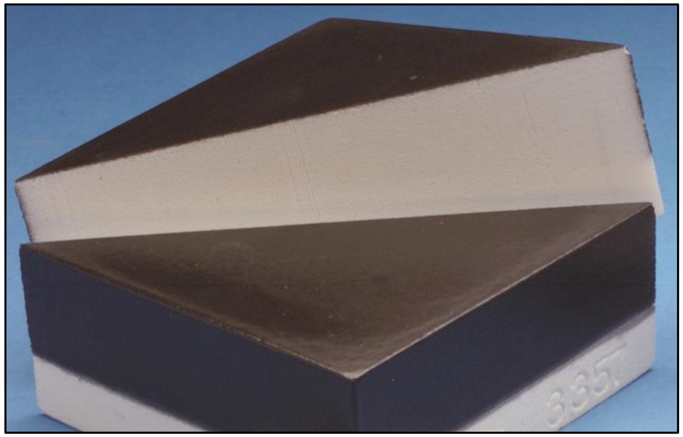
Launch Date
3/11/08

Coatings – Reaction Cured Glass (RCG)

Description: Black coating consisting of tetra-boronsilicide and low porosity borosilicate glass. Typically applied to top and sides to protect the porous silica. RCG is very effective on silica-based tiles up to 3000° F.

RCG-M is a modified version of RCG with a higher temperature capability (operates up to 3150° F).

Typical Application/Heritage: Most Shuttle tiles and many X-37b tiles were/are coated with RCG.



Shuttle era RCG coated tile

RCG coated TUFROC tile at ~ 3000° F during an arc jet test

RCG coated tile from an R&D activity

Surface Treatments – TUFI, HETC

Surface Treatment: Toughened Unipiece Fibrous Insulation

Description: Consists of borosilicate glass ($B_2O_3.SiO_2$), silicon-boride (B_xSi), and molybdenum disilicide ($MoSi_2$), yielding a stronger, tougher silica tile.

Heritage: Standard TUFI tiles were used on the Shuttle Orbiter's underside. White variants with higher impact resistance and conductivity were used on the upper body.

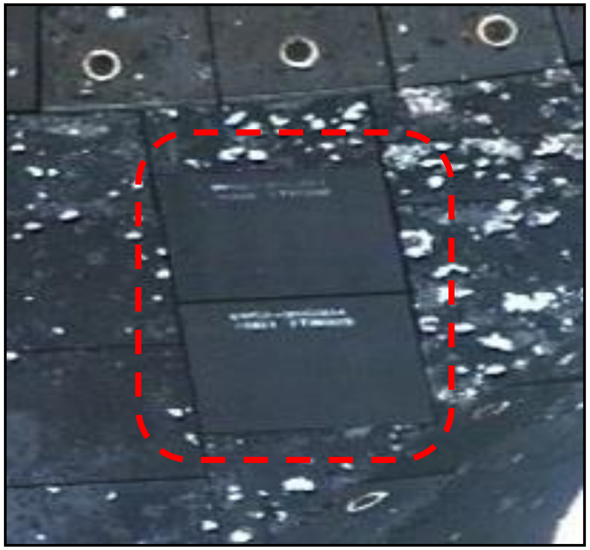
Shuttle era TUFI treated tile

Surface Treatment: High Efficiency Tantalum-based Composite

Description: Similar to TUFI except that HETC includes tantalum disilicide ($TaSi_2$).

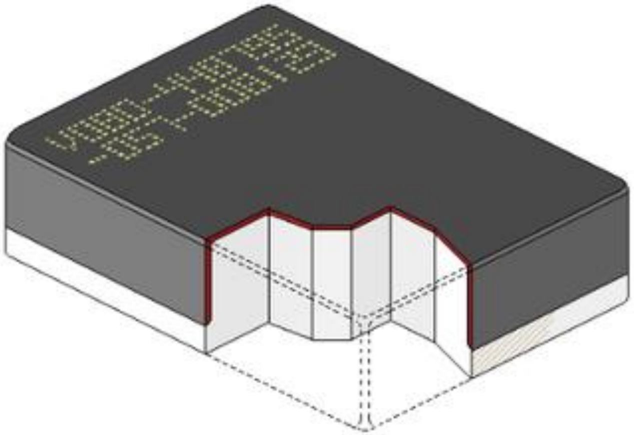
Designed to operate at higher temps than TUFI and to mitigate higher thermal expansion differences between the substrate and coating.

Heritage: Three X-37b missions.

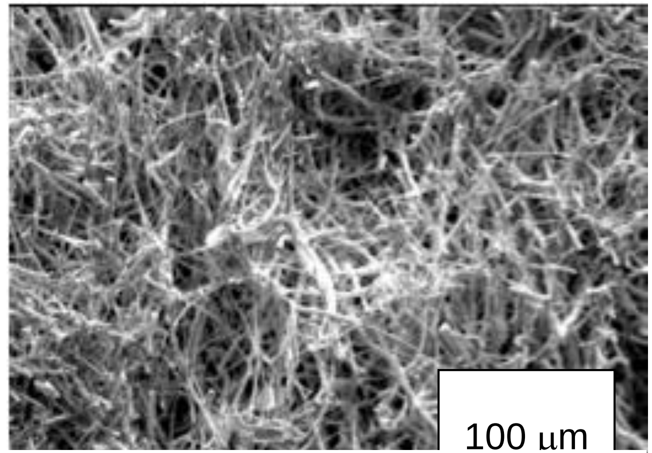


TUFI tiles undamaged after 3 flights

Reusable TPS: Tiles and Coatings

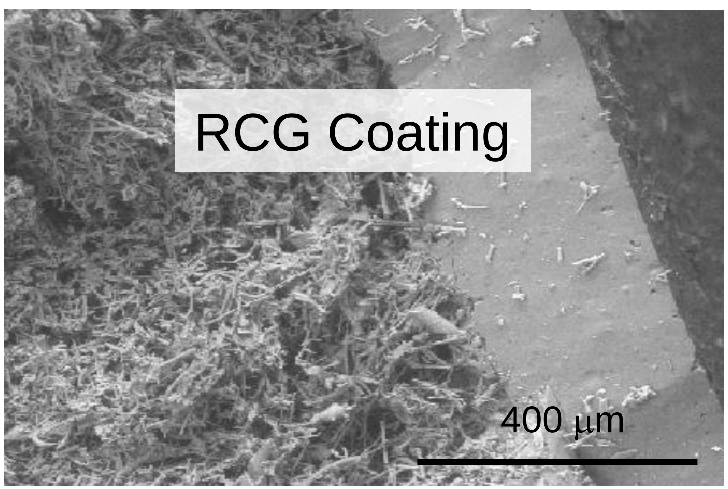


Density: 0.14 to 0.19 g/cm^3

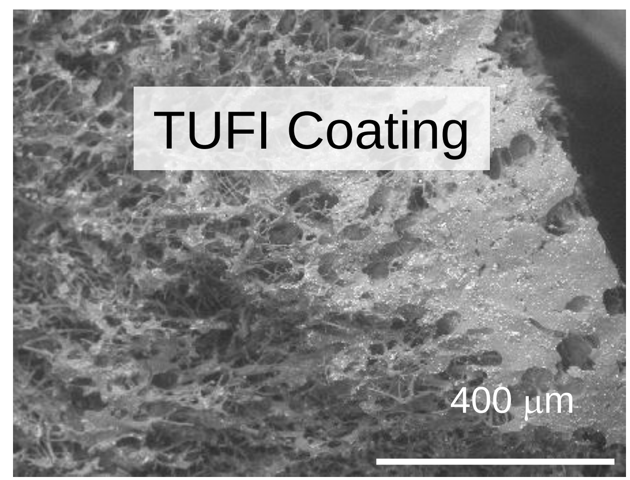


- Silica-based fibers
- Mostly empty space- >90%porosity

“Space Shuttle Tile”

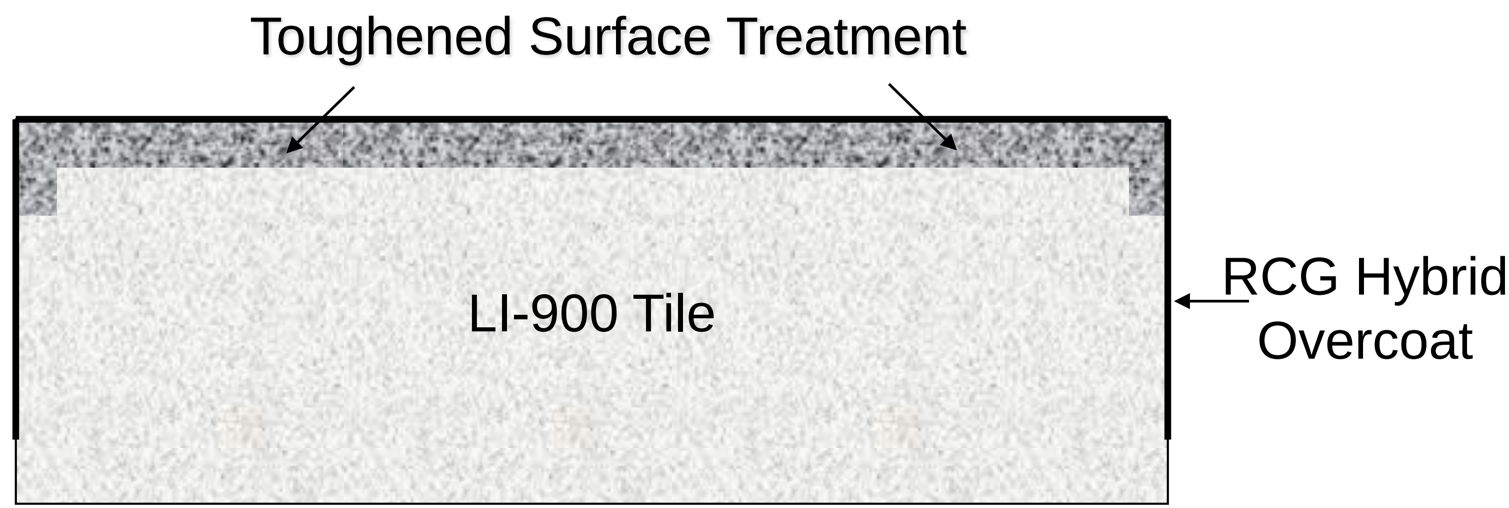


- RCG is a thin dense high emittance glass coating on the surface of shuttle tiles
- Poor impact resistance



- TUFI coatings penetrate into the sample
- Porous but much more impact resistant system

Optimized LI-900/TUFI

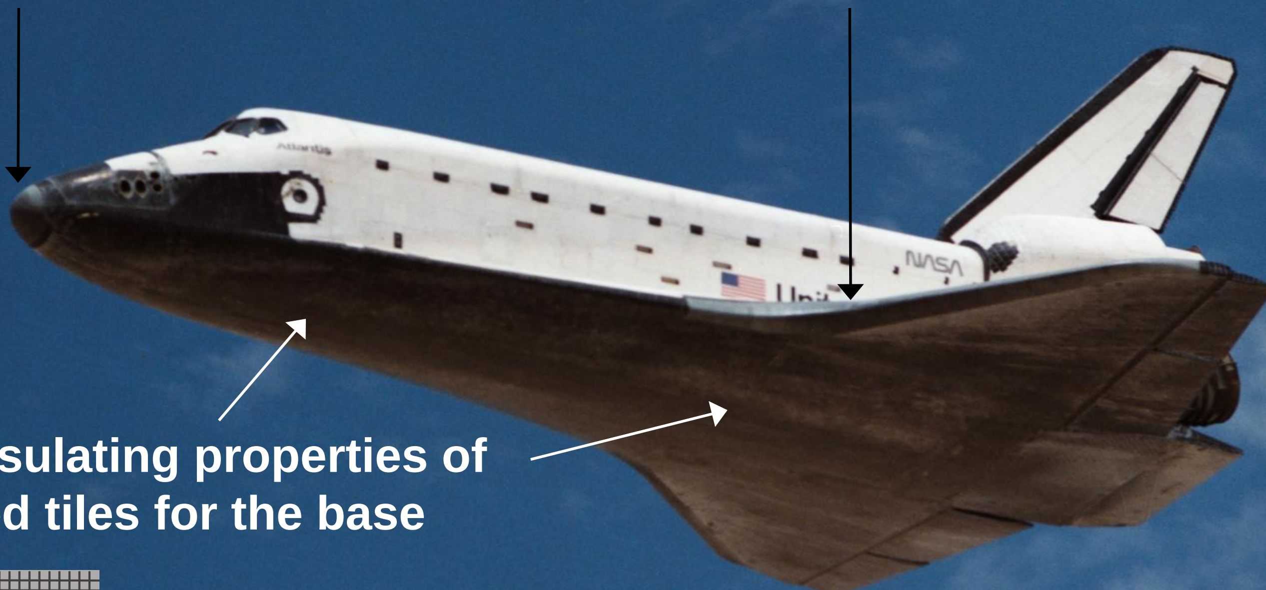


This system reduces the weight of TUFI/LI-900 to an acceptable level by limiting the area where the surface treatment is applied while retaining the improved damage resistance of the TUFI system.

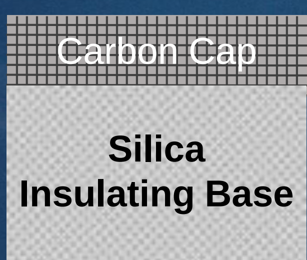
TUFROC Background: Initial Concept

3 decades of Space Shuttle experience led to the concept for an advanced reusable thermal protection system

TUFROC is a 2 piece system that takes advantage of the high temperature capability of carbon for the cap



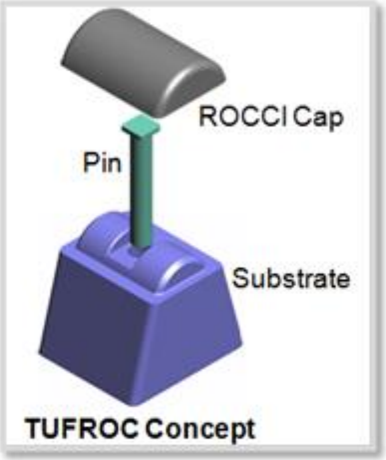
with the insulating properties of silica based tiles for the base

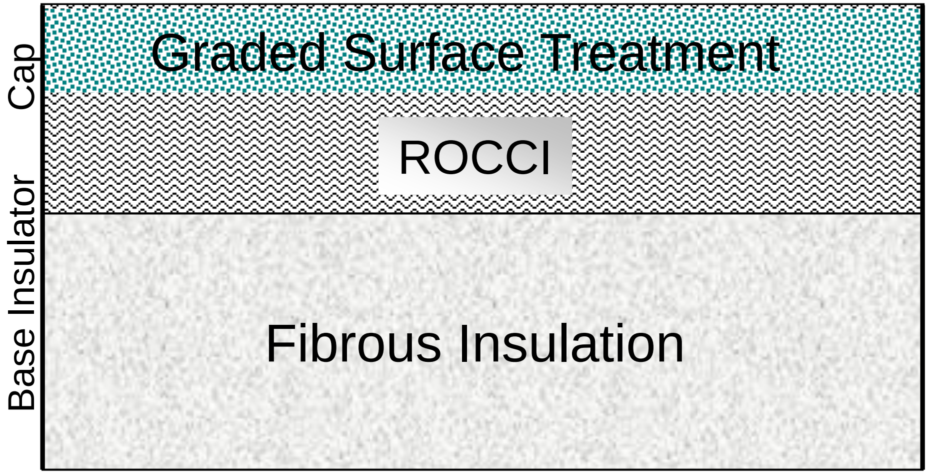


TUFROC TPS

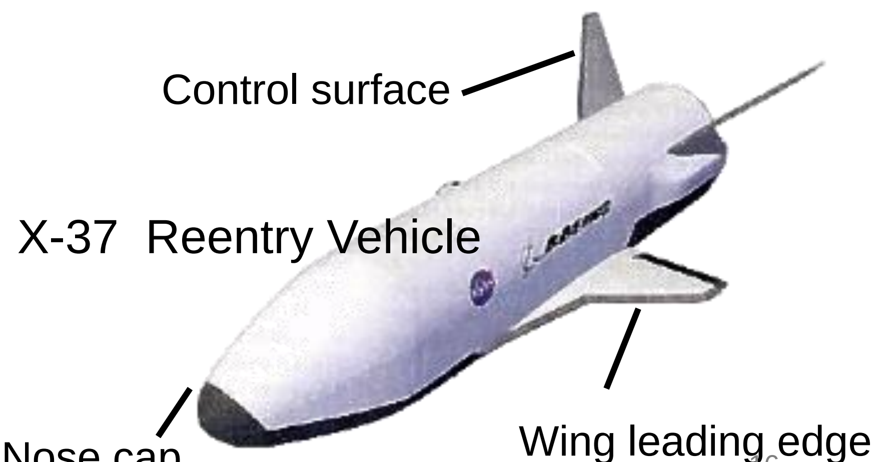
(Toughened Unipiece Fibrous Reusable Oxidation Resistant Ceramic)

- Developed TUFROC for X-37 application
- Advanced TUFROC developed recently
- Transferred technology to Boeing and others
- System parameters:
  - Lightweight (similar to LI-2200)
  - Dimensionally stable at surface temperatures up to1922 K
  - High total hemispherical emittance (0.9)
  - Low catalytic efficiency
  - In-depth thermal response is similar to single piece Shuttle-type fibrous insulation





Schematic of TUFROC TPS



TUFROC Background: Initial Concept

TUFROC 2-piece system

Basic Approach

Re-radiate enough heat so that conduction across
- Cap is within temp limits of the insulating Base
- Base is within temp limits of the Vehicle

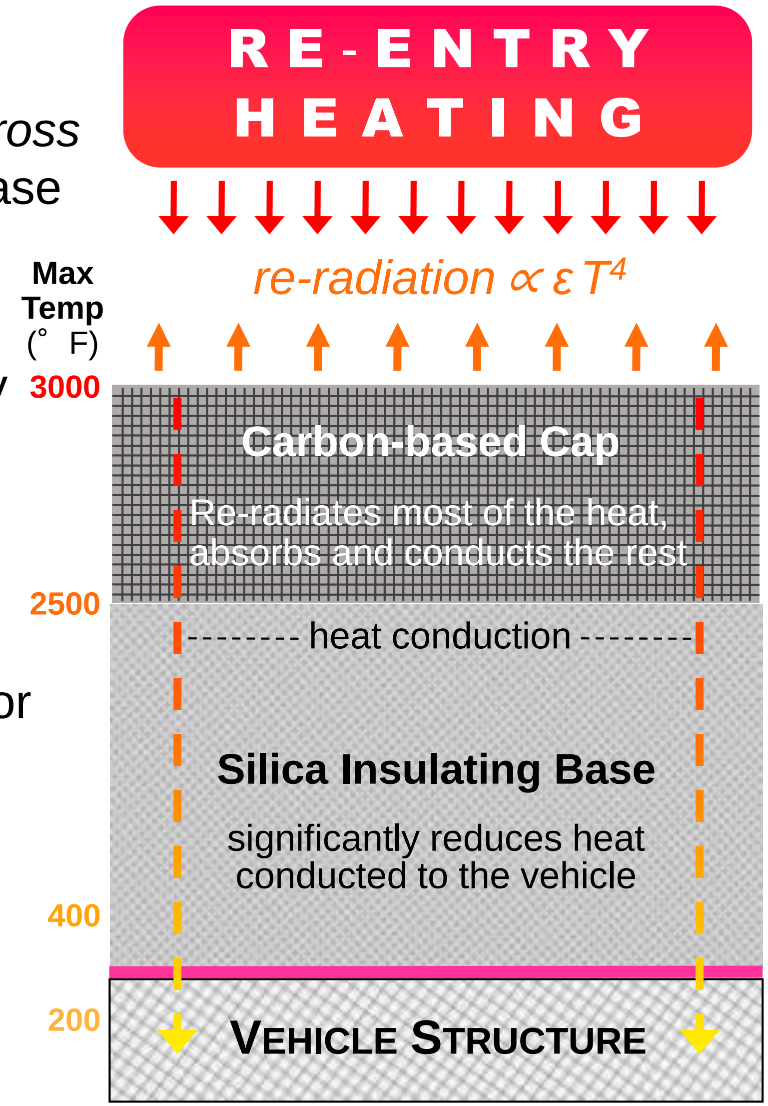
Carbon Cap

Low density carbon with a high temp capability
- unprotected carbon will rapidly oxidize

Silica Insulating Base

Starting point was LI-900 Shuttle tile
- outstanding, low weight silica based insulator
- mechanically weak
- breaks down above 2300° F

TUFROC Concept



TUFROC Background: Initial Concept

TUFROC 2-piece system

Basic Approach

Re-radiate enough heat so that conduction through

- Cap is within temp limits of the insulating Base
- Base is within temp limits of the Vehicle

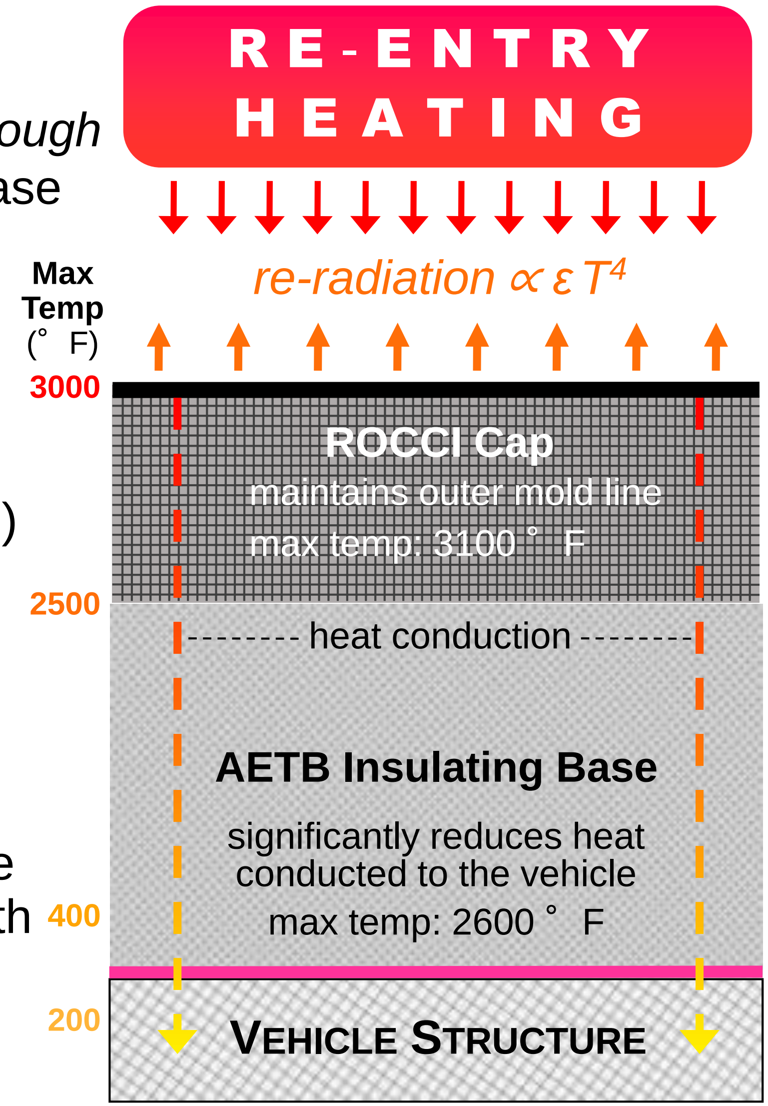
ROCCI Carbon Cap

- Silicon-oxycarbide phase slows oxidation
- HETC treatment near surface slows oxidation and keeps emissivity high (ε ~ 0.9)
- Coated with borosilicate reaction cured glass (RCG) for oxidation resistance

AETB Silica Insulating Base

- Solved thermo-structural issues by adding boron-oxide (B_2O_3) and alumino-borosilicate fibers, which also tripled mechanical strength
- Increased temp capability to 2500+ ° F by adding alumina (Al_2O_3) fiber

TUFROC Design



Advanced TUFROC

2 Piece Approach

Re-radiate enough heat so that conduction through
- Cap is within temp limits of the insulating Base
- Base is within temp limits of the Vehicle

ROCCI Carbonaceous Cap

- Silicon-oxycarbide phase slows oxidation
- High temp HETC surface treatments that helps mitigate ROCCI – RCG CTE issues
- Improved, higher viscosity RCG to handle repeated cycles at higher temperatures

AETB Silica Insulating Base

- Solved thermo-structural issues by adding boron oxide (B_2O_3) and alumino-borosilicate fibers, which also improved mechanical strength
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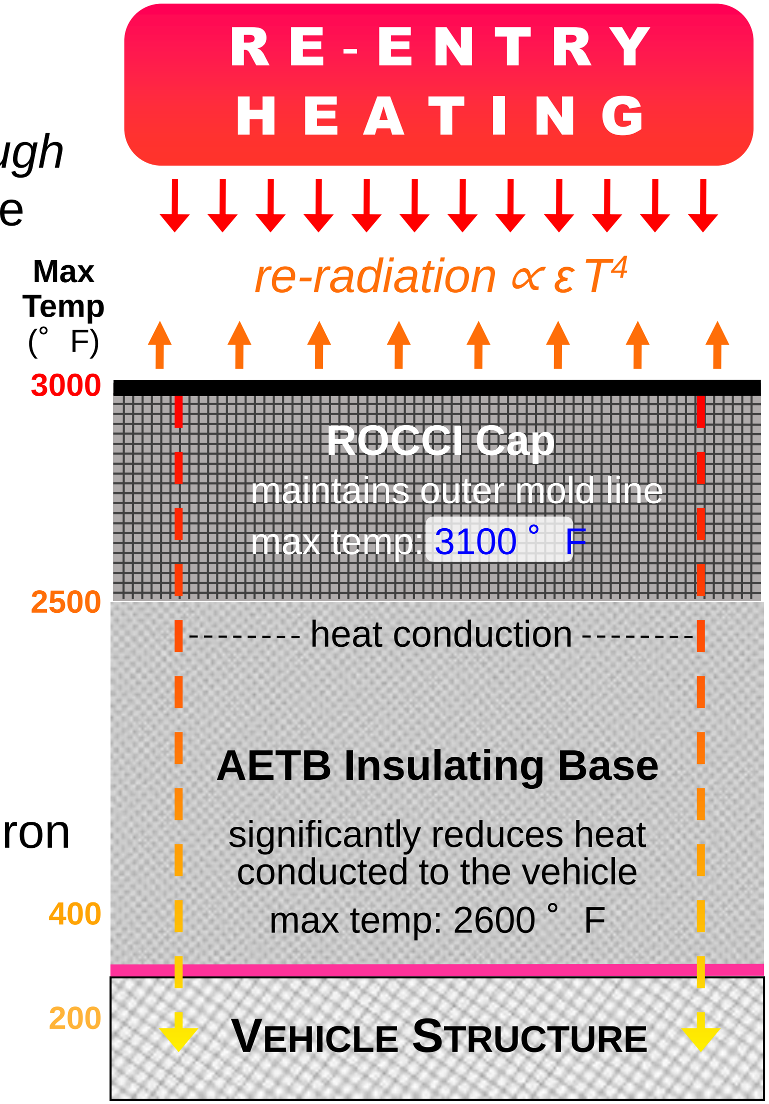
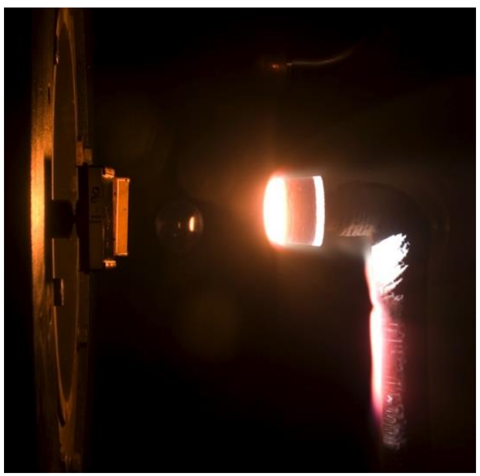


Series of Arc jet tests conducted to evaluate modified HETC, RCG.

Blunt cone provides uniform temps across stagnation region of the model
(more useful for evaluating different surface treatments / coatings than blunt wedges)

AHF T-257 (Jul 2007) Blunt cones at 0.04 atm and 78 W/cm^2

1st Exposure
5 min



2nd Exposure
5 min

Total exposure = 600 sec

Model 1025

3080 °F

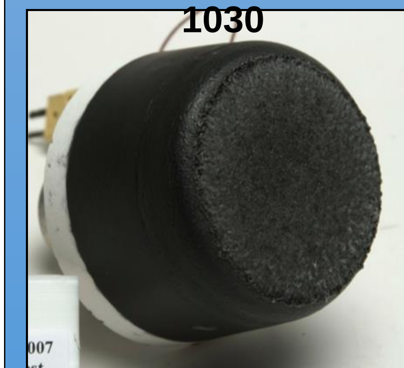
3100 °F

Model 1028

3070 °F

3090 °F

Model 1030



3095 °F

3060 °F

TUFROC: Toughened Uni-piece Fibrous Reinforced Oxidation-resistant Composite

Description: Carbon cap attached to a silica based insulating tile base with HETC

surface treatment and a modified RCG coating. Cap is typically < ½" thick and consists of carbon fiber substrate impregnated with silicon-oxysilane (aka ROCCI) that has a density of 0.57 g/cc. Silica base is AETB-like tile.

Typical Applications

Reusable TPS for LEO re-entry on wing leading edge, nose area, and control surfaces with environments < 3100° F. Higher heat fluxes and temperatures are possible if duration is limited to a few minutes or ablation/single use is acceptable.

Heritage: Three X-37b successful LEO re-entries. Baselined for SNC Dreamchaser wing leading edge, nose area, and control surfaces.

X-37b with TUFROC wing leading edge

* winner of NASA's Invention of the Year

TUFROC R&D Success!

- Repeatable arc jet testing of the modified TUFROC demonstrated a multiple use capability
- Modified TUFROC material and processing specification frozen and branded as Advanced TUFROC
- Technology transfer of Advanced TUFROC has started with Boeing and Sierra Nevada Corporation

Standard TUFROC performed better than expected as demonstrated by a successful re-flight of X-37b wing leading edge tiles

credit USAF

X-37b, April 2015

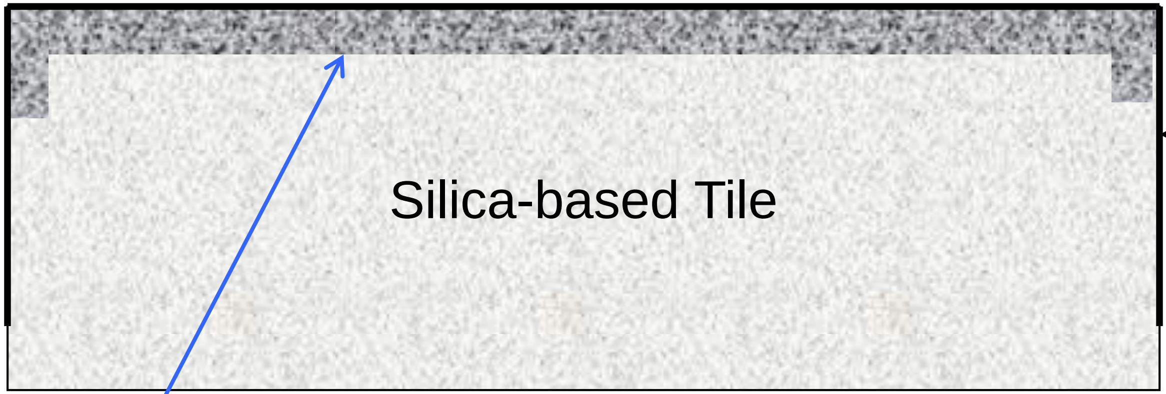
Summary

- Coatings and surface treatments on reusable TPS
  - RCG, TUFI used extensively on shuttle
  - Technology now being used for new materials system
- TUFROC
  - Uses refinements of coating and surface treatments from shuttle era to make a 2 piece material for leading edges
- Reusable materials still used on back shells and other low-heaiting areas of vehcles such as Orion.

National Aeronautics and
Space Administration

Ames Research Center
Entry Systems and Technology Division

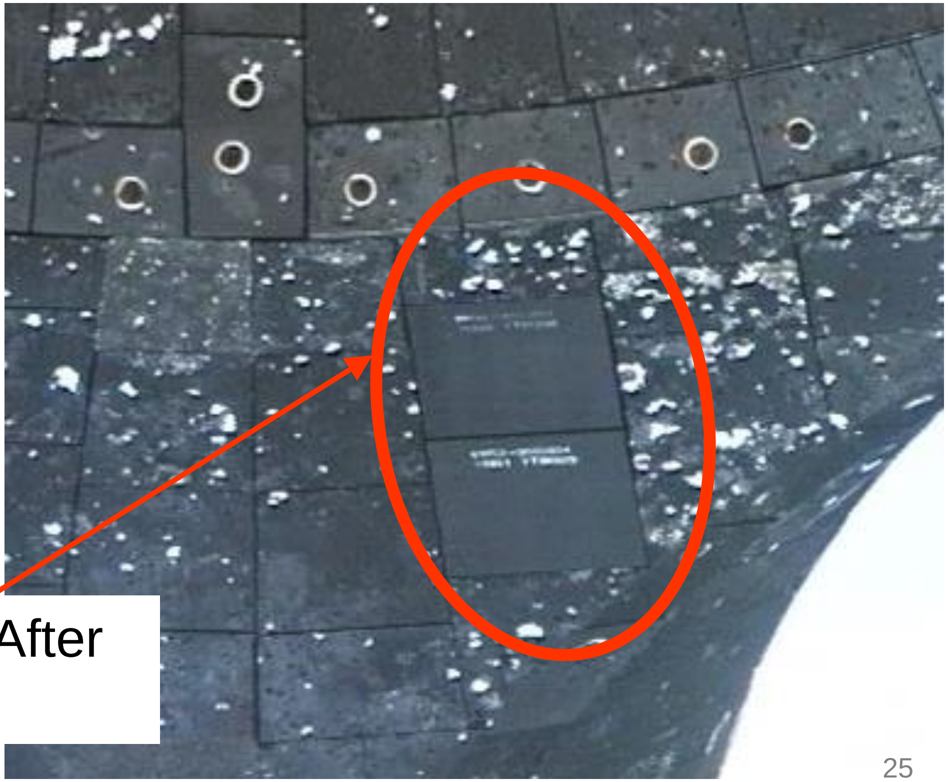
Shuttle Flight Testing of TUFI Tiles in Base Heatshield



RCG Hybrid Overcoat

Impregnated surface treatment

TUFI tiles used on base heatshield of Shuttle to protect against damage from debris incurred during liftoff



TUFI/AETB-8 Tiles Undamaged After Three Flights